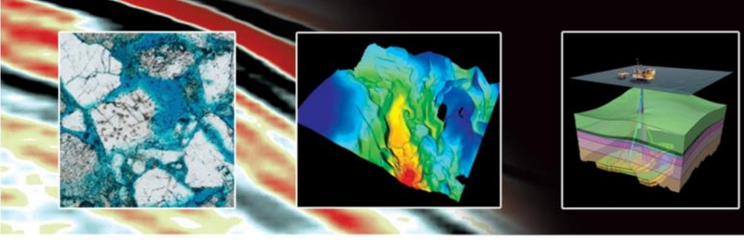

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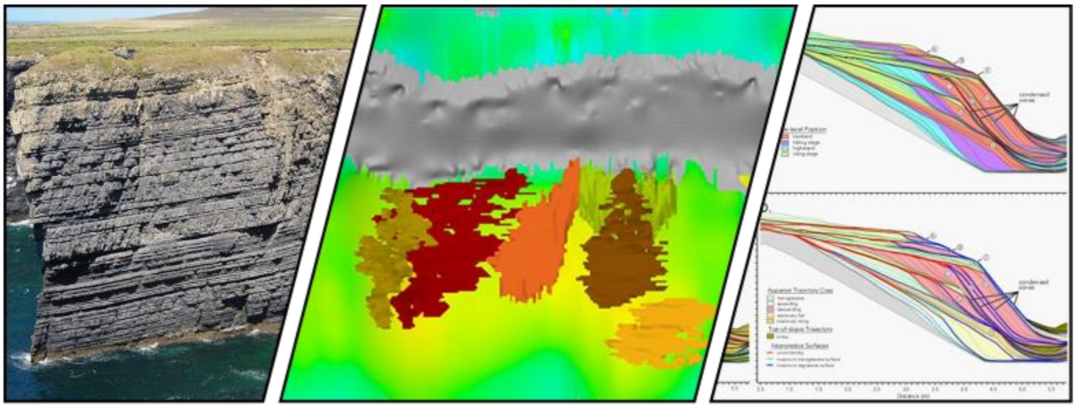
Abstract Book

Stratigraphy in Modern Geoscience:

methodologies, application and future relevance

23-24th Jan 2024

The Geological Society, Burlington House, Piccadilly, London



Understanding stratigraphy has been fundamental starting point for any geoscientist seeking to explore a sedimentary basin, play, prospect, or field. This conference will focus on the role and importance in the 21st century of the subdiscipline of stratigraphy within geoscience, especially to early-career geoscientists working in subsurface evaluation. In previous decades the petroleum sector provided abundant opportunities for application of stratigraphy, for example to reduce uncertainty in hydrocarbon exploration and production. As these traditional applications become less relevant through the ongoing energy transition, what new roles for stratigraphy will emerge? The aim of this conference will be to explore this question. Rather than focus on a specific region or geological theme, this conference will instead celebrate the ongoing power of stratigraphy to contribute to society. Presentation and discussion will focus on the state-of-the-art in core stratigraphic principles and methods, and explore how those principles and methods can continue to be applied to contribute across academic and industrial sectors through the energy transition and beyond.

This two-day conference will bring together industry and academic groups to present and discuss the latest applications of stratigraphy in modern geoscience. The event will be a mix of keynote talks, presentations, poster sessions, and panel discussions. The organisers welcomes papers on the following themes:

- Does traditional stratigraphy still apply in modern geoscience?
- Digital outcrop models, applications, and unfulfilled potential?
- AI and machine learning: a benefit or hazard?
- Future directions in stratigraphy through the energy transition and beyond

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Stratigraphy in Modern Geoscience: methodologies, application and future relevance

23rd January 2024

Burlington House and Virtual via Zoom

Programme

	Day One
08.30	**Registration**
09.00	**Welcome**
	Session One: Is traditional stratigraphy still useful?
09.10	**KEYNOTE: Stratigraphy at the forefront of geoscience** **Sietske J. Batenburg, *University of Barcelona***
09.40	**Stratigraphy into the future** Mark Brownless, *CTO, Geoteric*
10.00	**Long and short term glacio-eustasy as potential key driver for deposition ofreservoirs in the Moray Firth Basin** Douwe G. van der Meer, *CNOOC Europe Petroleum Limited*
10.20	**BREAK**
10.50	**Digital Biostratigraphy: Data-driven Techniques and Tools for Biostratigraphic Interpretation** Peter Kiss, *CGG*
11.10	**Bringing Realistic Stratigraphy into Evolutionary Biology through Age-Depth Modeling** Niklas Hohmann, *Utrecht University*
11.30	**Revisiting the stratigraphic modelling component of the geomodelling workflows for CCS projects such as the Decatur Project in the Illinois Basin** Thomas Jerome, University of Calagary
11.50	**Discussion & debate - Future directions in stratigraphy?**
12.20	**LUNCH**
	Session Two:
13.20	**KEYNOTE: Quantitative Virtual Outcrop Geology** John Howell, *University of Aberdeen*
13.50	**The Unfulfilled Potential of Digital Outcrop Data in Stratigraphy** Dave Hodgetts, *VRGeoscience Limited*
14.10	**CarboKitten: a forward models of carbonate platform growth for testing hypotheses on time - and - space completeness of the stratigraphic record** Johan Hidding, *Netherlands eScience Center*
14.30	**BREAK**
	Session Three: Digital outcrop models: potential unfullfilled?
15.00	**KEYNOTE: Descriptive Geology using Deep-Learning: What's the Catch?** **Cedric John, *Imperial College***

15.30	**Digitalization and artificial intelligence applications to biostratigraphy – a new world?** Gil Machado, *Chronosurveys*
15.50	**Automated correlation of chemostratigraphic well data from the Rockall Basin, UK** Kilian Eichenseer, *University of Durham*
16.10	**Discussion & debate - Future directions in stratigraphy?**
16.40	**Closing**
16.50 – 17.50	**Drinks Reception**
	End of Conference

Posters
Seismic Stratigraphy Interpretation of Late Albian-Early Turonian Successions in Southwest Iran: Implications for Reservoir Characterization and the Potential Stratigraphic Petroleum Play Mostafa Sabouhi
The influence of subaerial denudation on carbonate platform stratigraphy architecture Xianyi Liu
Long-Term Phanerozoic Global Mean Sea Level: Insights from Strontium Isotope Variations and Estimates of Continental Glaciation Douwe G. van der Meer

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ORAL ABSTRACTS
(In Programme Order)

Session One: Is traditional stratigraphy still useful?

Keynote – Sietske J. Batenburg, University of Barcelona

Stratigraphy at the forefront of geoscience

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Stratigraphy forms the backbone of studies of sedimentary sequences, as it allows us to connect separate geologic sections. This has enabled the investigation of different processes and phenomena that shaped the Earth on a common time scale, from a local to a global perspective. As a field, stratigraphy is evolving into an interdisciplinary domain, where information from different sources such as palaeontology, chemistry and astrophysics is combined to elucidate the processes driving Earth system dynamics.

Only a century ago, stratigraphy was limited mostly to the recognition of characteristic rock units and fossils to recognize and trace geologic strata. Nowadays, these pivotal fields are complemented by the study of sequences, cyclicity, seismic data, magnetic signals and chemical components, including isotopic systems. Integrated Stratigraphy is the combined application of multiple stratigraphic disciplines, including Lithostratigraphy, Biostratigraphy, Sequence stratigraphy, Cyclostratigraphy, Seismic stratigraphy, Magnetostratigraphy and Chemostratigraphy. This multiproxy approach can provide detailed and reliable age and duration constraints (Chronostratigraphy), enabling the study of depositional processes and their tectonic and climatic drivers on robust age models.

This presentation aims at demonstrating the relevance of stratigraphy in a changing world, with examples of paleoclimate studies. With the advent of deep-sea drilling, a new era of high-resolution investigation of past global change initiated. Now, stratigraphic techniques increasingly allow correlation between the marine and terrestrial realm. Together, information from the oceans and the continents can enable us to understand the response of the Earth system to past hothouse climates and carbon cycle perturbations, which can act as analogues for the current climate crisis.

Stratigraphy into the future.

Dr Mark Brownless

CTO, Geoteric

mark.brownless@geoteric.com

Abstract text for oral presentation

Stratigraphy is the essence of geology. Geology is critical to solving many of the world's major issues. Thus, stratigraphy has a critical piece to play in the future.

Knowing where a thing is, what it is, and how to find more of it, or even to avoid it, is important. The reason why you might want to ask such questions may change, but the necessity to be able to answer such questions remains constant. Carbon Capture and Storage projects will require a better understanding of the earth than E&P projects ever did, and this will rely on stratigraphic understanding.

One of the earliest maps of Britain is the Gough map dating from the 14th century. I imagine at the time of completion of that map they felt that it was job done. It's unlikely they imagined the quality of Ordinance Survey or all the advances that lead to Google Maps. Perhaps this is where we are with geology and stratigraphy today, we have the British Geological Survey maps (and apps), but we have yet to fully realise something like "Google stratigraphy".

Wiliam Smith's work in the late 18th and early 19th century gave us a beautiful and informative map of the UK, and whilst there must have been a question of what next upon the map's completion, we now know there was much more to come, that famous map was not the end of stratigraphy but just the beginning.

The future of Stratigraphy, as for so many other disciplines, will be driven by data, technology, and the minds of (wo)men. Geoscience has been working with 'large data' for decades. Seismic volumes of GB and TB have been available for many years. The change that is upon us is the use of AI to analyse data and assist the geoscientist to make sense of it, to efficiently turn it into information, then into understanding and ultimately to decisions.

In figure 1, AI has been used to identify the faults and the horizons in the seismic data. Although difficult to see at the scale of the image there are several differences between what is shown in the image and the usual interpretation results using the traditional approach. First the image shows the seismic data volume can be interpreted completely, from top to base, or if preferred interpreted for a stratigraphically defined region. Second the quality of the interpretation is very high. Third the time taken to achieve such results is a few days or less.

Using AI, we examine seismic and well data making features previously invisible visible. The clarity seen in the depositional edge of the mass flow deposit in figure 2, allows us to see an almost fractal termination to some of the flows. Interpreting this by hand would be very challenging, the AI approaches used here can examine every data point, of looking in all directions, understanding the impact and locations of faults, and understanding sediments

are deposited on top of each other in a sequence. An echo of Nicholas Steno and the law of superposition from the 17th century.

This high level of accuracy and thorough analysis has already shown that what may appear simple is sometimes not. Figure 3 indicates that a stratigraphic analysis must consider the full 3D nature of faulting to have a hope of coming to the correct conclusion. Using the new AI workflows we reveal, often for the first time, features in fields that have been worked for many years. Such difficult to identify features often explain the occasional unexpected performance of a field or of a surprise drilling result that may otherwise be difficult to understand.

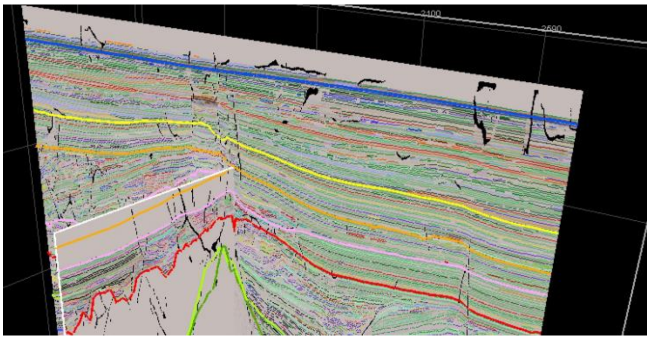

Figure 1: the complete seismic volume has been interpreted and results displayed on two intersections at right angles (note there are thick lines and very thin lines), one with the complete volume, and one with a stratigraphically restricted zone.

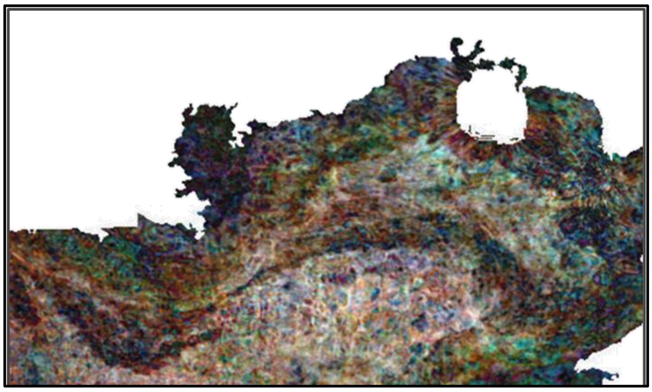

Figure 2: A very high quality, high-resolution interpretation produced by a Geoteric AI Horizon interpretation of an internal reflector in a mass flow deposit. The horizon is draped with a frequency blend indicating thickness or compositional variations.

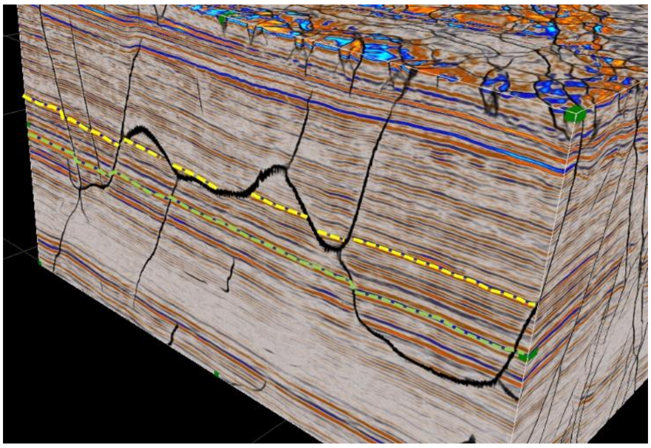

Figure 3: Sometimes a simple looking structure can be misleading. Without the accurate 3D AI Fault interpretation, it would be very tempting to push a very simple horizon interpretation through this data set which would be incorrect.

There is more information and understanding to be extracted from seismic data, and well data, than we were previously able to obtain, and this will need stratigraphy to understand it.

Sadly, for us this is a long way from walking the hills with a hammer, a notebook, and a hand-lens. But on the bright side, like technological change often does, it will cause us to learn more about our subject the Earth and in particular stratigraphy. I wonder if we are seeing the emergence of a new branch of stratigraphy, perhaps Data Stratigraphy, or is that too much?

This abstract contains information provided by the North Sea Transition Authority and/or other third parties.

Long and short term glacio-eustasy as potential key driver for deposition of reservoirs in the Moray Firth Basin

Douwe G. van der Meer, Dean Gagnon, John Millington

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Global mean sea level (GMSL), or eustasy, is a key driver for passive margin stratigraphy, and GMSL reconstructions have been made since at least the 1970's based on stratigraphy. However, these reconstructions have been hotly debated as basins and their associated (sequence)-stratigraphy may not represent a global signal. In addition, the source data (wells, seismic) is generally not disclosed and is therefore impossible to verify. Plate tectonic modelling has been able to constrain tectonic eustasy at first order but is limited by the lack of preserved oceanic crust prior to the Jurassic. Hence eustatic reconstructions remain poorly constrained. A novel, independent method based on isotope geochemistry, was recently published (Van der Meer et al. 2022) yielding a Tectono-Glacio-Eustatic (TGE) curve, focussing on the two key drivers of GMSL. The method assessed plate tectonic eustasy (i.e., mid-ocean ridge spreading) using the well-established strontium record. Long-term glacio-eustasy was estimated using a recent compilation of global average paleotemperature derived from $\delta^{18}O$ data. In combination with paleogeographic reconstructions, ice volumes on land and continental shelf margins were estimated. Eustatic sea level variations associated with long-term glaciations (>1 Myr) reach up to ~90 m, whereas plate tectonic-derived eustasy reached up to 150m amplitude. Several passive margins (without tectonics) that are of importance to hydrocarbon exploration have been tested, and mega-sequences as defined by wells and seismic, are consistent with the derived TGE curve.

On shorter timescales (<1 Myr), Milankovitch glacio-eustatic cyclicity affects GMSL. This is relatively well constrained for the Quaternary, and well understood for the Late Cenozoic icehouse. Further back in time, orbital motions are poorly constrained, but it is generally assumed that these must have occurred in similar manner. In combination with presence of land ice at high-latitudes, short-term glacio-eustasy must have occurred too. However, repeated patterns of sedimentary strata are not always the result from Milankovitch cyclicity but may also have been caused by autogenic controls, therefore the deduction of any allogenic control from stratigraphy remains ambiguous.

We therefore test whether both the long-term and short-term eustatic cyclicity, as predicted from the TGE curve, is recognisable at field scale for several fields in the Moray Firth Basin, which occupy different times and settings in the Moray Firth basin. We demonstrate that novel insights are obtained, which may lead to future opportunities. Other explanations exist, but we find that glacio-eustasy may have been the only driver that is needed to explain the timing of deposition of these Late Jurassic-Early Cretaceous reservoirs.

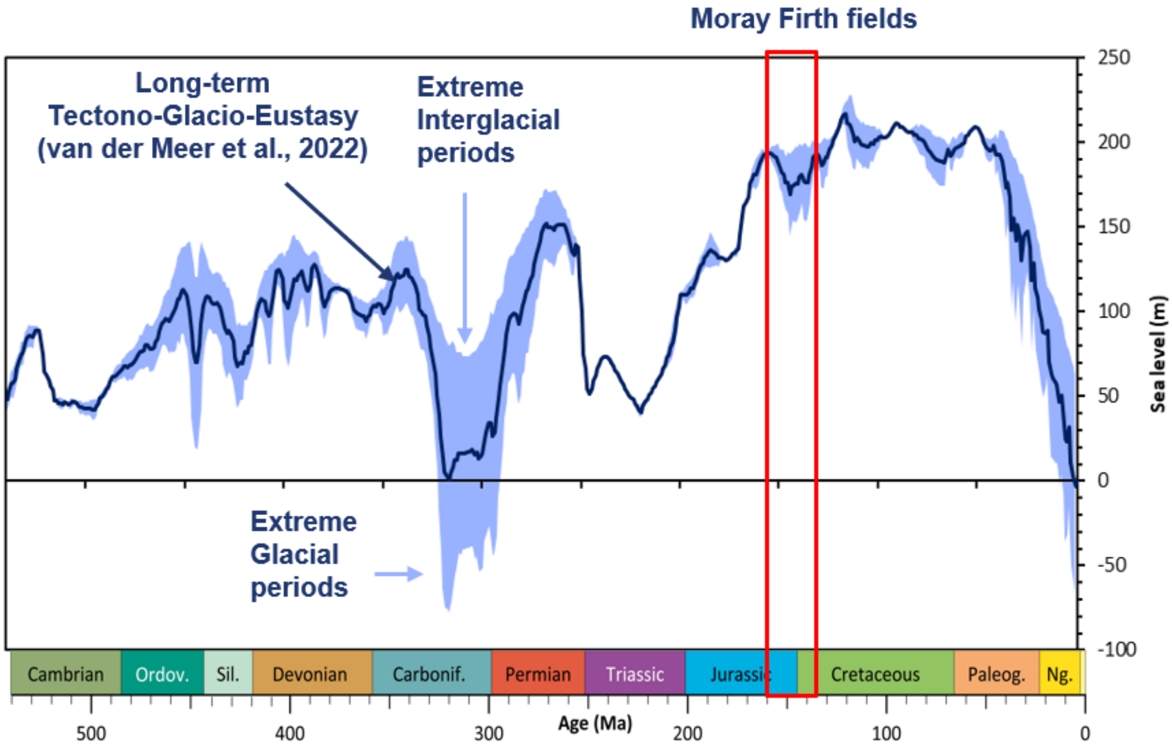

Figure 1: Tectono-Glacio-Eustatic curve with timing of Moray Firth Fields

Digital Biostratigraphy: Data-driven Techniques and Tools for Biostratigraphic Interpretation

Kiss Peter, Clayton Jennifer, Cullum Joshua and Lee WenJun

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Biostratigraphic data is essential for geological interpretations by allowing the spatial and temporal correlation of geological formations. Large quantities of legacy biostratigraphic data are available however, with constantly adapting chronological timescales and detailed biozonations varying across the industry, it is often difficult to ensure that datasets are interchangeable. Since updating vintage datasets might be challenging and ineffective timewise, biostratigraphic datasets are often unchanged and inconsistently stored, hindering the use of legacy datasets in future studies. Here, we introduce a novel workflow that combines data engineering and data science techniques that can update or re-interpret biostratigraphy, at a single or at multiple well locations.

In this case study, legacy well data was used and applied to a well in an attempt to revise and update the stratigraphic interpretation. The selected well harbours a diverse assemblage of planktonic foraminifera and nannofossils, comprising around 1000 unique species, ranging from the Early Eocene to the Middle Miocene. Initially, species counts and their corresponding depths were extracted from legacy stratigraphic charts using data engineering techniques and updated to modern synonymies (Fig. 1). The data extraction phase was followed by automated detection of caved and reworked specimens, which was done by studying the normal distribution (with 98% confidence intervals) of each species in the assemblages. After removing the outliers, diagnostic taxa were used from the entire assemblage to determine the biostratigraphic events, as some non-marker species caused noise in the interpretation. The interpreted key events were correlated with in house dictionaries in order to assign absolute ages to every determined 'TOP' and 'BASE' biostratigraphic event. In the last stage, four outlier detection algorithms (Isolation Forest, Random Sample Consensus, Local Outlier factor and Histogram Boosting) were used to determine inaccuracies, in which to each biostratigraphic event a confidence value was assigned. The confidence values had to be higher than a defined threshold to be considered in situ in our final interpretation.

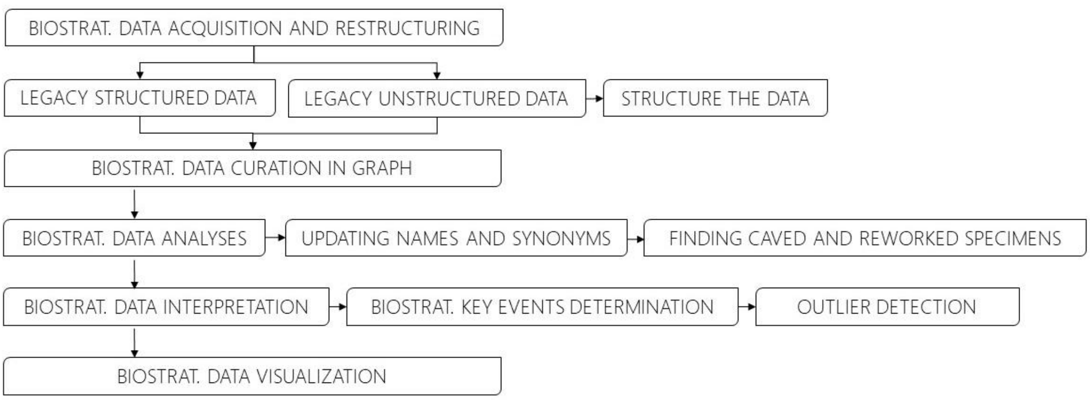

Figure 1. Flow chart illustrating the methodological steps involved in the digital biostratigraphic workflow, which begins with the biostratigraphic data acquisition and restructuring, and is followed by the implementation of data science techniques for data interpretation and visualization.

The accuracy of the introduced digitalized workflow was evaluated by correlating the output with the standard biostratigraphic approach that follows the manual interpretation, without using data science techniques (Fig. 2). This comparison revealed that the digital interpretation was able to determine the chronostratigraphy with normalized root mean squared error (NRMSE) = 15.84 m for the Neogene intervals, whereas larger inaccuracy appeared for the Paleogene intervals (NRMSE = 35.28 m). The discrepancy of the predictive workflow resulted from a less-comprehensive Neogene events dictionary, especially for the Late Eocene, and a lack of integration of other geological disciplines, which are involved in the standard interpretation. Despite the discrepancy, these results show that the digitalized workflow is capable of providing a relatively accurate (NRMSE = 32.28 m) and quick insight into the stratigraphy, while the whole digital workflow requires less than 30 seconds per well.

Intervals	Standard interpretation [m]	Digital interpretation [m]	RMSE [m]
Middle Miocene	3510	3530	-20.0
Early Miocene	3560	3570	-10.0
Late Oligocene	3730	3740	-10.0
Early Oligocene	3840	3880	-43.4
Late Eocene	4155	4075	80.0
Middle Eocene	4410	4415	-5.0
Early Eocene	4970	4980	-10.0
Late Paleocene	5450	5450	0.0
Early Paleocene	5632	5635	-3.0
Late Cretaceous	5700	5740	-37.5
RMSE [Root Mean Square Error] = 32.28 m			

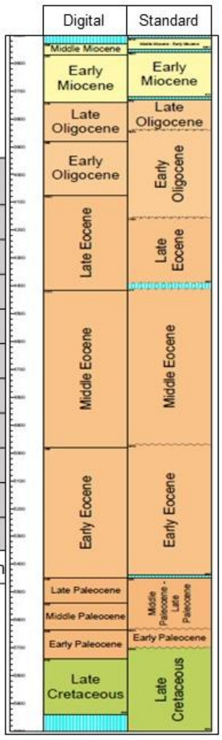

Figure 2. Comparison between the outputs of the manual and digital biostratigraphic workflows. The digital workflow was capable to re-interpret the biostratigraphy at the studied site within a very short time (less than 30 seconds), with ~35 m discrepancy.

Bringing Realistic Stratigraphy into Evolutionary Biology through Age-Depth Modeling

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The stratigraphic record allows observation of fossil evolution over longer time scales than are accessible to direct human observation. However, direct dating of fossils in deep time is impossible, making it necessary to estimate their age from indirect methods. The age inference is complicated by stratigraphic effects such as changing sedimentation rates and hiatuses. Age-depth models assign chronological ages to stratigraphic positions, thus establishing a temporal framework for the fossils they contain, but are themselves dependent on stratigraphic architectures. A robust understanding of these architectures is fundamental for establishing realistic, accurate age-depth models, and reconstructing evolutionary change from the fossil record.

We present a novel mathematical framework for age-depth modeling implemented in the R software. It includes two non-parametric methods to estimate age-depth models from complex stratigraphic data and to quantify the associated geochronological uncertainties. In contrast to other age-depth modeling frameworks, it allows to directly transform complex data structures and mathematical objects such as phylogenetic trees and time series from the time domain to the stratigraphic domain and vice versa. As examples of the developed framework, we

1. construct age-depth models for Devonian strata in the La Thure section, Belgium, using sedimentation rates constrained by cyclostratigraphic methods.
2. use measurements of extraterrestrial ^{3}He from ODP site 960 (Maud Rise, Weddell Sea) to construct age-depth models for the Paleocene–Eocene thermal maximum.
3. examine the preservation of phylogenetic relationships along the onshore-offshore gradient in a carbonate platform simulated in the CarboKitten model.

The presented framework simplifies the interface between stratigraphy and other domains of science, making it easier for communities outside of sedimentology to understand and use stratigraphic information in inter-disciplinary approaches. It demonstrates that a modern, model-driven understanding of stratigraphy is highly relevant to all disciplines drawing information from geohistorical records.

Revisiting the stratigraphic modelling component of the geomodelling workflows for CCS projects such as the Decatur Project in the Illinois Basin.

Thomas Jerome, Department of Earth, Energy, and Environment, University of Calgary, thomas.jerome@ucalgary.ca

Per Kent Pedersen, Department of Earth, Energy, and Environment, University of Calgary

A geomodel is a three-dimensional (3D) grid capturing our understanding of the reservoir, its overall statistics (porosity, permeability…), but also the lateral continuity of its high-permeability geobodies and of its barriers. In oil and gas projects, wells are often kilometers apart, making it often impossible to correlate the stratigraphic details from well to well. Geostatistics are then heavily used to model such reservoirs. In CCS projects, it doesn't have to be that way. Observation wells drilled close to CO2 injectors allow to characterize the details of the stratigraphy locally. For geomodels to capture such high-resolution details, the geomodeller must be ready to spend more time on the gridding process before running geostatistics. Otherwise, the reservoir will be locally misrepresented.

Introduction.

In the deep geological units targeted by CCS projects, before such projects start, pre-existing wells are found usually drilled kilometers to tens of kilometers apart. It makes it difficult, if not impossible, to track subtle stratigraphic changes between wells so far apart. These uncertainties are usually captured with geostatistical techniques as part of the stratigraphic modeling in geomodelling projects. Geostatistics are a key aspect of any geomodelling workflow.

But CCS projects have the unique trait that their Measurement, Monitoring and Verification (MMV) plans include drilling observation wells very close to the CO2 injectors. That unusually high density of well data (injector + associated observation wells) makes it possible to characterize the stratigraphy locally at high-resolution. This is very important as the CO2 displacement between the injector and its observation wells will be heavily impacted by the local architecture of flow units and baffles.

This presentation revisits the stratigraphic modeling component of the geomodeling workflow for such CCS projects. The goal is to see if the traditional geostatistical approaches are the right way to capture such high-resolution stratigraphical details. This analysis is done using the public data, models and reports of the CCS Decatur Project located in the Illinois Basin (USA).

Data and Method.

The Decatur CCS Project, located in the Illinois Basin (USA), ran from 2007 to 2021. The project injected and monitored 1 million tons of CO2 in the Cambrian aged Mount Simon Sandstone. The data, models and reports of this project are available online free of charge (Decatur, 2022).

High-resolution stratigraphical details can be correlated across the 4 wells of the project (2 pairs of injector and observation wells). Figure 1 shows the correlations for the Lower Mt Simon Sandstone between the wells CCS1 and its associated monitoring well VW1 (light grey, red, green, blue, and orange correlations). The deeper correlations (red to orange) seem to correlate with how the CO2 migrated from the injector towards the monitoring well, showing the interest to taking the time to include those correlations in the geomodel.

The team behind the Decatur Project used a traditional geomodeling approach based on geostatistical simulation of the well logs, combined with a cube of seismic attributes. Similar methods are here compared with our own approach where the high-correlation details are integrated in the 3D grid itself, before using geostatistics.

The models are compared in two ways. Firstly, by simple visual inspection on how they each capture the vision that the asset team had about the stratigraphy of this reservoir. Secondly, by running flow simulation to see how the CO2 is moving in each model through time. The goal is to see what, beyond the pure visual difference between the models, impacts how the CO2 is migrating in the reservoir.

Result and Discussion.

As will be shown during the presentation, integrating the high-resolution details of the correlation into the mesh of the 3D grid greatly help respecting the reservoir details between the wells. On the contrary, using geostatistical simulation techniques such as Sequential Gaussian Simulation in a traditional way, that is in a 3D grid built using thick zones, can be problematic. Such mesh doesn't allow "connecting" tight rocks together between the wells (nor the narrow high-porosity sands). This study shows that the geomodeller needs to take the time to work the mesh of the 3D grid instead of "rushing" to geostatistics.

Misrepresenting the geobodies in a CCS project is problematic. It might give a false idea on how the CO2 will remain in the reservoir. Such misrepresentation could go as far as decreasing the confidence of the public in the project, in case of significant discrepancies between the predictions and the reality. In CCS projects, high-resolution stratigraphic interpretation is essential. And it is as important to use geomodelling techniques which capture those details.

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Laronga, R., Swager, L. and Bustos, U., 2023. Time-lapse pulsed-neutron logs for CCS: what have we learned from all these monitoring runs? 64th SPWLA Annual Logging Symposium.

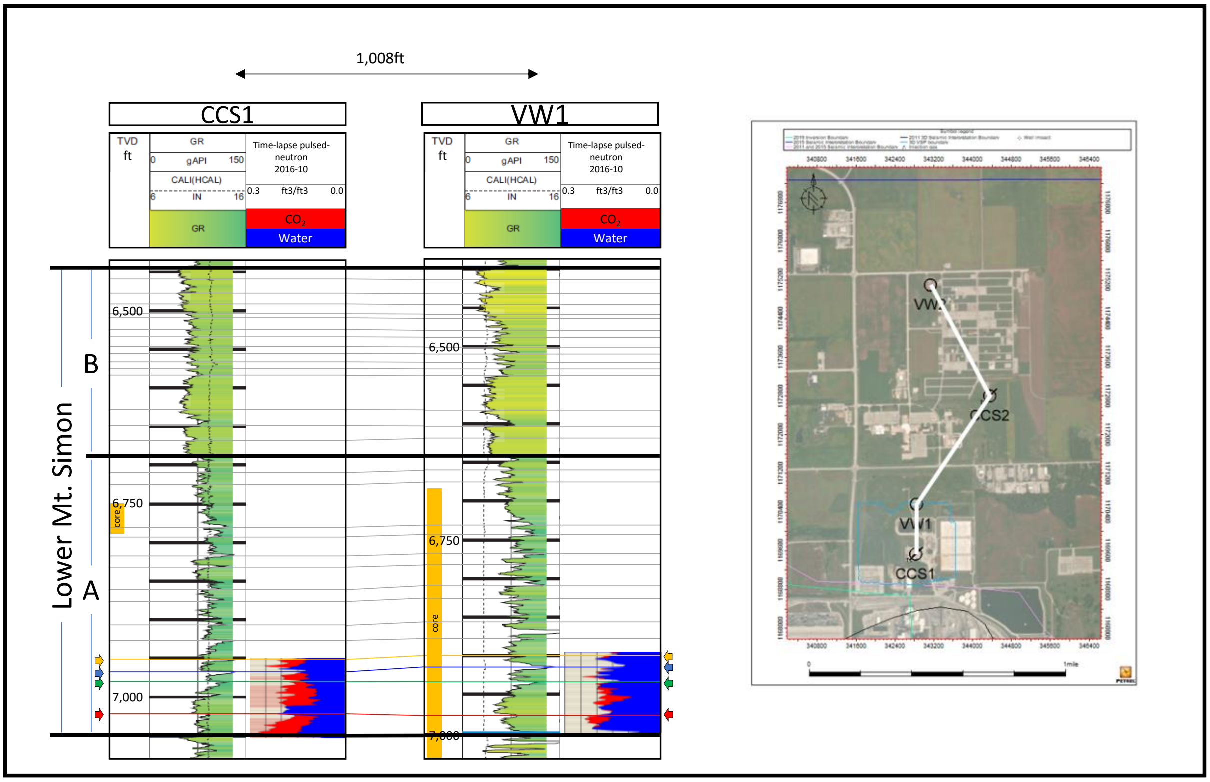

Figure 1. High-details GR correlation between CCS1 and VW1 (light-grey lines + red, green, blue, orange lines near the base). Relationship of GR correlation and CO2 plume growth as of Oct 2016 from the injector CCS1 towards the monitoring well VW1 (modified from Freiburg et al. 2014 and from Laronga et al. 2023).

Keynote - John A Howell

Quantitative Virtual Outcrop Geology

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Over the past 20 years, virtual outcrop geology has involved from a niche research area into mainstream geological practice. Now, georeferenced, 3D photo-realistic virtual outcrop models can be easily collected with low-cost, easy to operate UAVs and processed on standard softwares. As such virtual outcrops have become standard data, routinely collected from the field with a wide variety of applications such as analogue studies for subsurface reservoirs and repositories and virtual fieldtrips. Early applications focused on using virtual outcrops to map key surfaces and to describe spatial relationships between sedimentary bodies. More recently, focus has shifted to utilising virtual outcrops to extract large volumes of statistical data that can be used to investigate geological processes, stratigraphic stacking patterns and to populate geostatistical models of analogues subsurface systems.

Large scale (>10 km) virtual outcrops provide statistically valid samples of depositional systems that can be used to derive statistically meaningful trends in stratigraphic stacking, such as channel-body distribution in distributive fluvial systems and large scale clinoform geometries, typically only observed in seismic data. Virtual outcrops are also used to build geocellular models of analogues for subsurface systems. This can be done in two ways, either by accurate mapping of key surfaces and the building of deterministic models of a specific outcrop, or by extracting geostatistics of the outcrop and using these to produce models. Geostatistical modelling methods use a number of statistical approaches including boolean (object-modelling) which require object dimensions; Indicator simulations, which require semi-variograms and, texture-based or multi-point statistics which utilise training images. This presentation will illustrate systematic approaches to extracting all of these data types from virtual outcrops.

In addition, a novel method for analysing facies proportions from virtual outcrop data will be presented. This method calculates the facies proportions from a series of equally spaced vertical profiles along the outcrop and the displays a probability density function for each facies. The spread of the pdf is a related to the lateral variability within the system. A narrow spread suggests the system is layer cake while a wider spread suggests a high degree of facies variability and equates to greater subsurface heterogeneity.

These approaches are illustrated with examples of data extracted from a range of virtual outcrops from continental, shallow marine and deep water clastic depositional systems.

The Unfulfilled Potential of Digital Outcrop Data in Stratigraphy

***Dr David Hodgetts*[1]** *and Dr Brian S. Burnham*[2].

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In recent years, advanced technology integration in geosciences has resulted in the rapid collection of high-resolution digital outcrop data. Techniques such as Light Detection and Ranging (LiDAR) and photogrammetry have facilitated the capture of large volumes of spatial data in relatively short time frames. These datasets are incredibly valuable for stratigraphic analysis. Digital outcrop datasets offer detailed insights into sedimentological processes, structural history, and basin evolution. Despite the surge in data acquisition and technological advancements, the full potential of digital outcrop data in stratigraphy remains unrealised.

Stratigraphy, at its core, seeks to decipher the temporal and spatial relationships of rock layers, or lithological units. Traditional field-based and analytical methods often involve manual on- site interpretation that may be limited by accessibility constraints. Digital outcrop models, however, provide comprehensive and accurate coverage of outcrops at unprecedented spatial resolution that enhances accessibility. This inherently facilitates greater interpretability of outcrops, thereby enhancing the understanding of facies transitions, depositional environments, and diagenetic alteration. Many challenges, however, impede their full integration into mainstream stratigraphic research.

Firstly, the sheer volume and complexity of digital outcrop data necessitate robust software solutions for effective visualisation and analysis. Integration of artificial intelligence and machine learning can expedite facies classification and sequence stratigraphy analysis, yet such initiatives are in their infancy.

Secondly, there exists a knowledge gap between traditional stratigraphers and digital geoscientists. Bridging this gap requires interdisciplinary training programs that equip geologists with skills in both stratigraphic concepts and digital data handling. Collaboration between academia and technology companies can pave the way for curriculum reforms and workshops aimed at this integration.

Lastly, the standardisation of data collection, storage, and sharing remains a pressing concern. With multiple stakeholders involved, from academic institutions to companies, establishing a universally accepted protocol for digital outcrop data management is imperative. Such standardisation would not only ensure data consistency but also promote collaborative research and data sharing across organisations.

While digital outcrop data presents a transformative potential for stratigraphy, a concerted effort is needed to harness its full capabilities. By bridging interdisciplinary knowledge gaps, and advocating for data standardisation, the geoscience community can usher in a new era of stratigraphic research that leverages the best of both traditional expertise and digital advancements.

CarboKitten: a forward models of carbonate platform growth for testing hypotheses on time- and -space completeness of the stratigraphic record

Johan Hidding[1], Peter Burgess[2], Xianyi Liu[3], Niklas Hohmann[3], Emilia Jarochowska[3]

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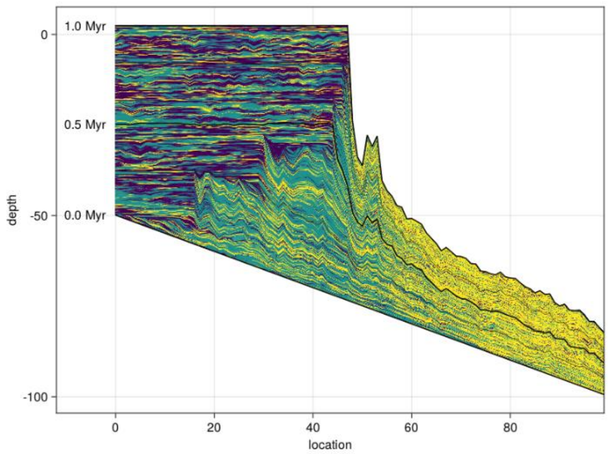
Stratigraphy of sedimentary strata is often dismissed as “more gaps than rock” and, at the same time, the only source of data for reconstructing the history of the Earth, its climate and biodiversity, etc. Crucially, the most common gaps, i.e. those which correspond to the highest proportion of missing time in the geological record, are too short (10^3 – 10^5 years) to be detected using dating tools available to stratigraphers. Quantifying the uncertainty of reconstructions of climate or biodiversity based on the stratigraphic record, requires estimating the distribution of such short gaps. Physical models of sediment formation and transform can be used to reproduce not an exact replica of a geological outcrop or basin, but an ensemble of reconstructions which allows estimation of the uncertainty of a reconstruction. They also allow testing hypotheses about the stratigraphic expression of known forcing mechanisms, such as glacial-interglacial transitions.

Here we present CarboKitten, an Open-Source version of the original stratigraphic forward model of carbonate platform growth, CarboCAT. We focus on carbonate platforms, because they are crucial for reconstructions of past biodiversity and their formation is driven by an interaction of physical and biological processes, leading to high spatial heterogeneity of sediments and stratigraphic gaps. The biological component of the spatial heterogeneity is modelled using cellular automata, the rules of which aim to approximate dispersal and competition between carbonate factories.

The primary motivation for creating CarboKitten (as opposed to using CarboCAT) is performance. The target is to create a large ensemble of simulations and infer the likelihoods of corresponding age-depth models. To this end we need a model that evaluates in the timespan of seconds to minutes. In the interest of open-science practices and inherent performance we chose to implement CarboKitten in Julia.



We discuss several aspects of the new implementation in more detail. By reimplementing CarboCAT we have the opportunity to alter sediment transport physics and add erosion.

We’ll also share some insights into using cellular automata for physical modelling in general, and as a consequence, the theoretical limitations of a model like CarboCAT/Kitten. Thanks to extensive documentation and to being Open Source, CarboKitten offers the scientific community the opportunity to contribute and widely adopt the forward simulation approach to testing stratigraphic hypotheses.

Keynote - Cédric M. John

Descriptive Geology using Deep-Learning: What's the Catch?

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Born in the classical era of "Natural sciences", stratigraphy is largely a descriptive science of facies and stacking patterns, ultimately leading to the interpretation of geological processes responsible for the observed pattern. Even today, and rock description remains pivotal for understanding our planet's past, present, and future. Despite this long tradition, extracting meaningful insights from rock description poses significant challenges due to the inherent complexity and variability of the data, the amount of existing material, and the subjectivity of the interpreter.

In my talk, I will first focus on the potential of computer vision with deep-learning to overcome many hurdles in descriptive geology. Focusing largely (but not exclusively) on carbonate rocks, characterized by their heterogeneity at all observational scales, I will discuss how computer vision transcends the traditional, tedious manual interpretations of cores, offering a rapid, and often more accurate, alternative for delineating depositional environments and sequence stratigraphy. Convolutional neural networks (CNNs) form the backbone of our approach, enabling my research group to process core data with improved efficiency and reproducibility. I will show that these sophisticated models, when correctly trained and fed with substantial datasets, serve as invaluable tools for geologists, outpacing conventional methods in speed without compromising on precision.

A will touch upon a very common issue in geosciences: the so called "small dataset problem", where the dataset size is too small for a deep-learning model to extract meaningful statistical features. To overcome this, we can turn to generative AI to oversample our training set, or use semi-supervised learning approaches. We successfully trained models on balanced dataset using generative AI, and on core deformation images from IODP with minimal labelled data using semi-supervised learning. We also successfully used generative AI in imaginative applications, for instance using Generative Adversarial Networks (GANs) to transform the resistivity images from formation micro scanners into representations mirroring actual core photographs, thus enhancing the interpretability for geologists irrespective of their background in downhole tools.

But every technology has a catch. In the second part of my talk, I will elaborate on what I see as the potential pitfalls of deep-learning. This will include issues similar to the ones faced by the field of statistics, i.e. the fact that the tooling has become very easy to use, but that without proper training on the underlying science, one can quickly come to wrong conclusions. I will also discuss other general concerns surrounding AI in general, such as data pollution, interpretability, and ethics.

Digitalization and artificial intelligence applications to biostratigraphy – a new world?

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Currently, in both academic and industrial studies, the analysis of microfossil samples for biostratigraphic uses is done by analysing slides under a microscope, by a specialist (usually with an MSc or Ph.D. in that field of expertise), who observes thousands of microfossils in each slide and may photograph dozens or hundreds of these. The types of analyses vary, but in most cases, these require quantified identification of different types of fossils, usually to species level. The analysis of each sample commonly takes several hours, with microphotographs taken for key microfossils. The process:

- Is laborious (not efficient)
- Does not allow capturing the whole slide as an image
- Is prone to different results when more than one user performs the analysis (may lack consistency)

Except for digital cameras and plotting software, the method has not significantly changed in over 100 years of micropaleontological studies.

Only recently has digitalization – by the use of high-resolution slide scanners, initially used in medical pathology – allowed the automation of some of the processes. Each slide produced from a geological sample typically contains thousands of microfossils. This technological breakthrough has also opened the door to the use of AI and specifically deep learning to automate image capture and identification of different types of microfossils.

Existing cases studies include image acquisition by standard microscopes (e.g. Gonçalves et al. 2016; Marcos et al., 2015), confocal microscopy (e.g. Romero et al., 2020), and high-resolution slide scanners (e.g. Punyasena et al., 2022), producing multi-Gb images followed by the application of CNN or similar techniques to identify types of microfossils (e.g. Dunker et al., 2021). The initial steps require building a training dataset by a specialist, which is used to train an AI model.

We developed a functional prototype to make the best use of these emerging technologies. The main goal of the project was to have a product that has high-resolution images of palynological slides as inputs and provides automatic quantified analyses of the several types of organic particles ready for interpretation – ternary diagrams, paleoenvironmental indexes, and kerogen types. Additional goals include the rapid visualization of particle types – e.g. all spores in a slide, to speed up taxonomic identification and biostratigraphic interpretation; data quality and interpretation quality control; and friendly (local or remote) access by users, including non-specialists.

For this purpose, we defined a training dataset, based on scanned versions of palynological slides of Chronosurveys' slide collection, ranging from Ordovician to Miocene, from 4 different continents. A few dozen slides were used, corresponding to thousands of palynomorphs. The training dataset s.s. that served as input for the AI model included 23 different particles (e.g. different types of phytoclasts, spores, pollen, dinocysts, AOM, freshwater and marine algae, etc) and was generated by annotating and labeling the particles by a specialist in a custom-made designed graphical interface.

After 10 initial images were annotated by the specialist, the model was able to segment (isolate from the background) and identify some of the most common classes. In subsequent images, the specialist validated the identification and segmentation or corrected it, in addition to identifying additional particles. Validation was based on a train-test split of the dataset.

For the AI model and user interface, a complex pre- and post-processing was created to handle the scanned data (files > 2GB). The scanned images are typically obtained in a proprietary format, which needed to be converted into an open format. This was performed with multi-threaded processing. The final user interface allows observation of the particles automatically annotated (segmented by coloured polygons) and QC the interpretation. Statistical analysis such as the number of particles and the area occupied by each particle is available, as well as customizable ternary plots and commonly used paleoenvironmental indexes (Figure 1).

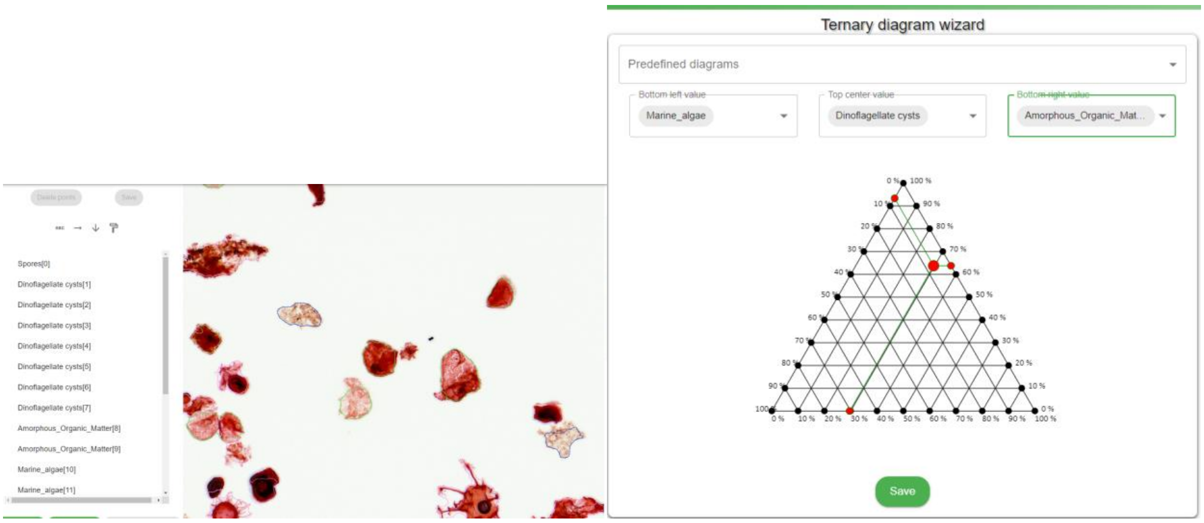

Figure 1 *User interface with the several classes automatically identified (left panel) and example of interpretation diagram (ternary plot).*

Acknowledgments

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Automated correlation of chemostratigraphic well data from the Rockall Basin, UK

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Correlation of well data is essential for constructing stratigraphic models that underpin the exploration for subsurface resources such as oil, gas, and geothermal energy. Most correlations rely on manually aligning records from multiple sections, using chemostratigraphic signals or geophysical data such as gamma ray or density logs. This process can be time-consuming and challenging.

Here, we present a novel algorithm designed to automatically align data from multiple wells based on their geochemical or geophysical signals. This method works by evaluating the fit of Bayesian splines to different alignments of the sections, using Markov Chain Monte Carlo methods to obtain the posterior distributions of the model parameters. Our method stands out from existing approaches, like dynamic time warping, by integrating more than two wells simultaneously, and by providing uncertainty estimates and multiple possible alignments. Additional data, such as prior information on sedimentation rates or unconformities can be easily integrated to further constrain the correlation.

We apply this method to chemostratigraphic data from six wells in the Rockall basin, northwest of Scotland. These data are primarily derived from Palaeocene sediments interspersed with varying amounts of volcanogenic material. To achieve stratigraphic alignments, we use elemental ratios and concentrations, e.g. Si/Al and Cr/Th ratios, and Fe and Mn concentrations. The results from our automated correlation are then compared with existing visual correlations.

POSTER ABSTRACTS

Seismic Stratigraphy Interpretation of Late Albian-Early Turonian Successions in Southwest Iran: Implications for Reservoir Characterization and the Potential Stratigraphic Petroleum Play

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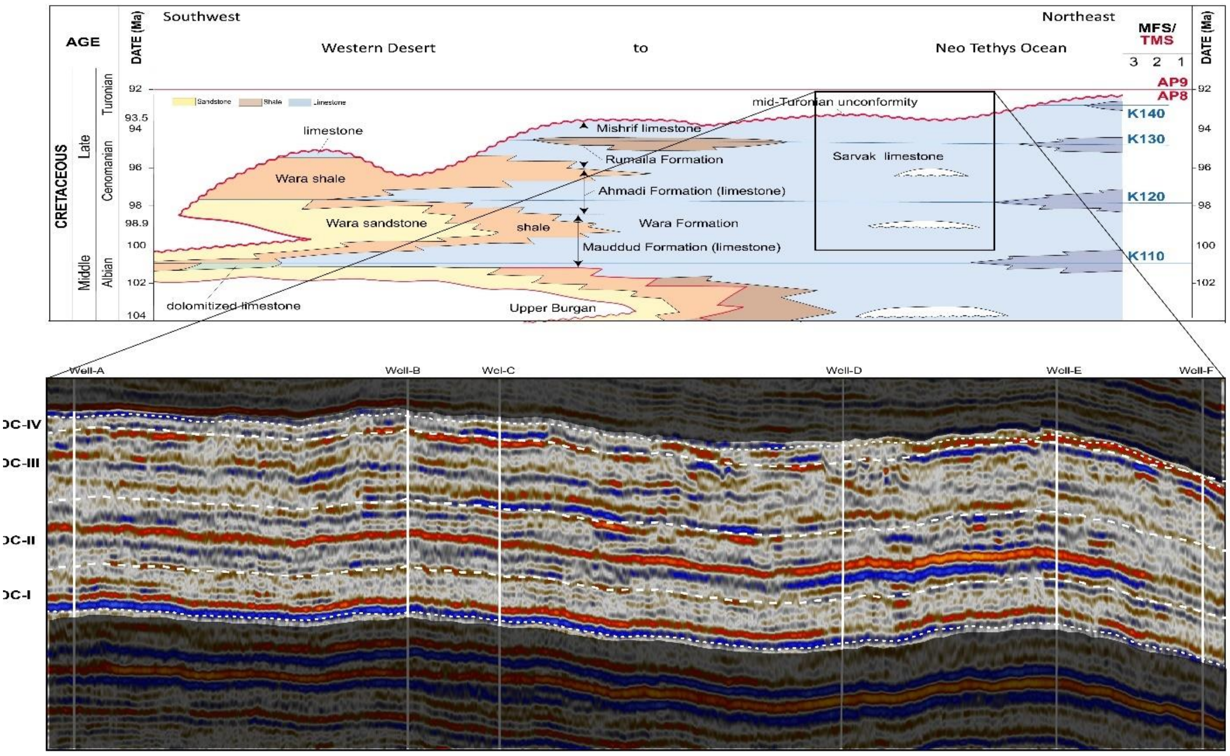
The Late Albian-Early Turonian succession in the Arabian Platform stands out as one of the world's richest hydrocarbon provinces. Despite a substantial body of literature on these successions, a comprehensive understanding of their potential Stratigraphical plays remains elusive, exacerbated by the absence of a seismic sequence stratigraphical architecture for southwest Iran, home to the largest and most productive Cretaceous accumulation. This study employs High-Resolution Seismic Sequence Stratigraphy (HRSS) to delve into the intricate stratigraphic layers of the Late Albian-Early Turonian successions. The investigation, drawing from data acquired from five wells, incorporates well logs, selected core data, biostratigraphical information, and chemostratigraphy analysis. Integration with a fully covered 3D seismic volume facilitates the identification of four 3rd-order sequences and multiple 4th-order sequences within the study area. Sequence-1 (DS-I), positioned in the Late Albian age, reveals Mudstone and bioclast wackestone indicative of an open marine environment. DS-I assumes significance as a key sequence, witnessing the disappearance of siliciclastic input from west to east within the studied region. DS-II (Early Cenomanian) and DS-III (Mid-Cenomanian) unfold on carbonate platforms with grain-supported facies in Shoal and Lagoonal depositional environments. Notably, a main and regional unconformity at the Turonian base, discernible on seismic sections, aligns with depleted values of δ18O on the Cenomanian-Turonian Boundary. The identification of maximum flooding surfaces in DS-I and DS-II enhances the stratigraphic interpretation.

Furthermore, the study reveals that reservoir facies exhibit lateral gradation and intercalation with non-reservoir facies at the 4th-order sequence scale. This observation underscores that the heterogeneity of reservoir facies is intricately governed by depositional processes operating within the context of 4th-order cycles. Highlighting the prospectivity of potential reservoirs, particularly within the Highstand System Tract (HST) of each 3rd sequence, the study emphasizes the significance of the HST in DC-III. In this locale, patch reef facies deposition is attributed to local tectonic activities and carbonate build-up movement, offering valuable insights into the geological processes influencing hydrocarbon reservoir formation.



Chronostratigraphical chart of the Albian-Turonian from southwest to northeast in the study area highlighted with the rectangle. Continuity of reflector in the seismic section that shows the paleogeography and thickness change across the section.

The influence of subaerial denudation on carbonate platform stratigraphy architecture

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The geological information preserved in strata is temporally heterogeneous and incomplete due to changes in depositional rates and hiatuses. This biases the estimations of the timing and rates of geological events (e.g., hyperthermals, mass extinctions, etc.) substantiallyhindering the understanding of the past and predictions on the future. Geologists do not always take this into consideration when interpreting data from strata, partly because of the lack of stratigraphic tools with sufficient resolution to quantify such incompleteness. Herein, we use a new Open-Source forward model for simulating carbonate platform architectures, CarboKitten, based on CarboCAT by Burgess (2013), to assess the effects of denudation on the incompleteness in preserved strata for geological reconstructions, such as biodiversity, geochemistry, paleomagnetism, and other types of geological records. We coupled different denudation models derived from geomorphological studies with the CarboKitten model and compared the outcomes. We also compared the results of denudation-coupled model to that of the model without denudation to assess how important a factor it is in the preservation of temporal records in carbonate platforms. The introduction of the denudation in the modelling of sediments architecture may contribute to ground-truthing reconstructions that rely on incomplete stratigraphic records and allow rigorous hypothesis testing of these reconstructions.

Long-Term Phanerozoic Global Mean Sea Level: Insights from Strontium Isotope Variations and Estimates of Continental Glaciation

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Ruben M. B. van de Weg
[CNOOC International]

Global mean sea level is a key component within the fields of climate and oceanographic modelling in the Anthropocene. Hence, an improved understanding of eustatic sea level in deep time aids in our understanding of Earth's paleoclimate and may help predict future climatological and sea level changes. However, long-term eustatic sea level reconstructions are hampered because of ambiguity in stratigraphic interpretations of the rock record and limitations in plate tectonic modelling. Hence the amplitude and timescales of Phanerozoic eustasy remains poorly constrained. A novel, independent method from stratigraphic or plate modelling methods, based on estimating the effect of plate tectonics (i.e., mid-ocean ridge spreading) from the 87Sr/86Sr record led to a long-term eustatic sea level curve, but did not include glacio-eustatic drivers. Here, we incorporate changes in sea level resulting from variations in seawater volume from continental glaciations at time steps of 1 Myr. Based on a recent compilation of global average paleotemperature derived from δ18O data, paleo-Köppen zones and paleogeographic reconstructions, we estimate ice distribution on land and continental shelf margins. Ice thickness is calibrated with a recent paleoclimate model for the late Cenozoic icehouse, yielding an average ~1.4km thickness for land ice, ultimately providing global ice volume estimates. Eustatic amplitudes (isostatically corrected) are ~200m for tectonics, and ~90m for glaciations (at timescales > 1 Myr), resulting in an overall ~250m range throughout the Phanerozoic. A comparison with other sea level curves is also made, and we discuss key differences in methodologies and outcomes. In summary, the published Tectono-Glacio-Eustatic curve provides a novel viewpoint on global climatological processes during the Phanerozoic and provides a useful background for understanding and interpretation of stratigraphy of passive margins.

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